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# UV RAMAN SCATTERING MEASUREMENTS OF A MACH 2 REACTING FLOW OVER A PILOTED CAVITY (POSTPRINT)

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**Propulsion Sciences Branch**
**Aerospace Propulsion Division**

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**14. ABSTRACT**
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# UV Raman Scattering Measurements of a Mach 2 Reacting Flow over a Piloted Cavity

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**UV Raman scattering measurements were made in a Mach 2 supersonic air flow over a cavity piloted with ethylene fuel ($C_2H_4$). The wall cavity simulated the pilot region of a scramjet combustor. In the UV Raman system, a 248 nm KrF excimer laser beam (400 mJ/pulse, 20 ns pulse length) was used to excite the Raman scattering in the combustion zone. Raman scattered light in the 254-278 nm spectral region allows measurement of the following molecular species: $CO_2$ (257 nm), $O_2$ (258 nm), $N_2$ (263 nm), $C_2H_4$ (268 nm), $H_2O$ (273 nm) and $H_2$ (277nm). To avoid damaging the fused-silica windows on the combustion test section: 1) the laser pulse was stretched from 20 ns to 150 ns using two optical delay cavities, 2) a long focal length lens (5 meters) focused the KrF beam to a relatively large diameter (1 mm diameter) and 3) the laser energy was decreased to 100 mJ/pulse. Under these conditions, the high power pulsed laser beam passed through the side fused-silica windows without inflicting damage. Raman scattered light was collected from the top fused-silica window and was focused into a 0.32 meter spectrometer that dispersed the Raman spectrum onto an intensified CCD camera. Multiple Raman spectra are obtained along an 8 mm line to yield spatially resolved measurements of chemical composition. By translating the optical table, Raman scattering spectra were obtained in a number of locations in the Mach 2 reacting flow over a piloted cavity. Raman measurements in ethylene-fuel rich zones were contaminated by laser-induced fluorescence interference from fuel derived species (e.g., polycyclic aromatic hydrocarbons). Additional problems included laser-induced fluorescence from the fused-silica windows and UV flame emission. The Raman scattering images are being analyzed to obtain information about fuel/air mixing and reaction under supersonic conditions. Efforts will be made to improve the UV Raman system for application to scramjet flows based on this first set of measurements.**

## I. Introduction

Advanced optical diagnostics are needed to understand supersonic fuel/air mixing and combustion in hypersonic propulsion systems. In particular, non-intrusive spatially- and temporally-resolved measurements of velocity, temperature, and chemical species concentrations are needed in scramjet flows to: 1) characterize the physics of mixing and burning of the air/fuel mixture at high-speed and 2) validate CFD models of scramjets.

Previously non-intrusive velocity measurements using hydroxyl tagging velocimetry (HTV) have been obtained in a scramjet model combustor in the AFRL Research Cell 19 at WPAFB (Pitz et al. 2005a,b; Lahr et al. 2006). In addition to velocity measurements, non-intrusive measurements of chemical species concentrations and temperature are needed in supersonic combustion for hypersonic propulsion to characterize fuel/air mixing and combustion. Pitz and co-workers have developed and applied UV Raman scattering to make "point" measurements of scalars in supersonic hydrogen-air combustion (Cheng et al. 1994). A narrowband KrF excimer laser was used to induce spontaneous Raman scattering in the supersonic flame to give measurements of major species concentrations ($H_2$, $H_2O$, $O_2$, $N_2$) and temperature. The ultraviolet laser produced increased Raman signal levels due to the 4$^{th}$ power dependence of the Raman cross-sections on the laser frequency. The major species concentrations were obtained by integrating the signal from the individual Stokes vibrational Raman lines. The Stokes to anti-Stokes ratio of the vibrational $N_2$ lines was used to determine the temperature. The species concentrations and temperature were

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measured along a 5 mm line to 0.4 mm resolution using an imaging Raman system (Nandula et al. 1994a,b). However, the UV Raman imaging system had never been developed for measurement along a line of chemical species concentration and temperature in a scramjet combustion flow. In this work, a line UV Raman system is developed and applied to a Mach 2 flow over a piloted cavity burning a hydrocarbon fuel, ethylene. The ethylene fuel simulates a cracked JP-7 fuel that would be used in a scramjet combustor (Puri et al. 2005).

## II. UV Raman Scattering System

The UV Raman system was initially set up at Vanderbilt University to characterize the system prior to transporting to AFRL. As shown in Fig. 1, a KrF excimer laser at 248 nm is used as the laser source owing to the greatly enhanced Raman signals at short wavelengths. To decrease the laser beam irradiance, a pulse stretcher is constructed as shown in Fig. 1. It has two optical delay cavities that are capable of stretching the original 20 ns beam to around 150 ns (FWHM). While this setup is effective in lowering the beam irradiance, it is susceptible to misalignment due to the long path length needed to stretch the beam to 150 ns (about 45 m). Consequently, all mirror mounts must be very rigid and insensitive to room temperature fluctuations. In initial measurements, the light is focused by a 1000 mm focal length lens into a test flow. A beam sampler is used to direct a small portion of the beam onto a pyroelectric joulemeter (J25LP) to monitor the relative pulse-to-pulse energy variations. The scattered Raman light is collected at 90º using two UV achromats (OptoSigma, f/4, 50 mm dia.) into an imaging spectrometer (J-Y iHR320, 0.32 m focal length, 2400 lines/mm holographic ion-etched 250 nm blaze grating). A long-pass liquid Butyl acetate filter is installed in front of the entrance slit, whose cutoff wavelength is ~255 nm. The dispersed light is collected by an intensified CCD camera (Princeton Instruments, 576x384, 200 ns gate, 25% quantum efficiency at 260 nm) and stored on a personal computer. The system timing is controlled by a DG535 pulse generator (Stanford Research Systems).

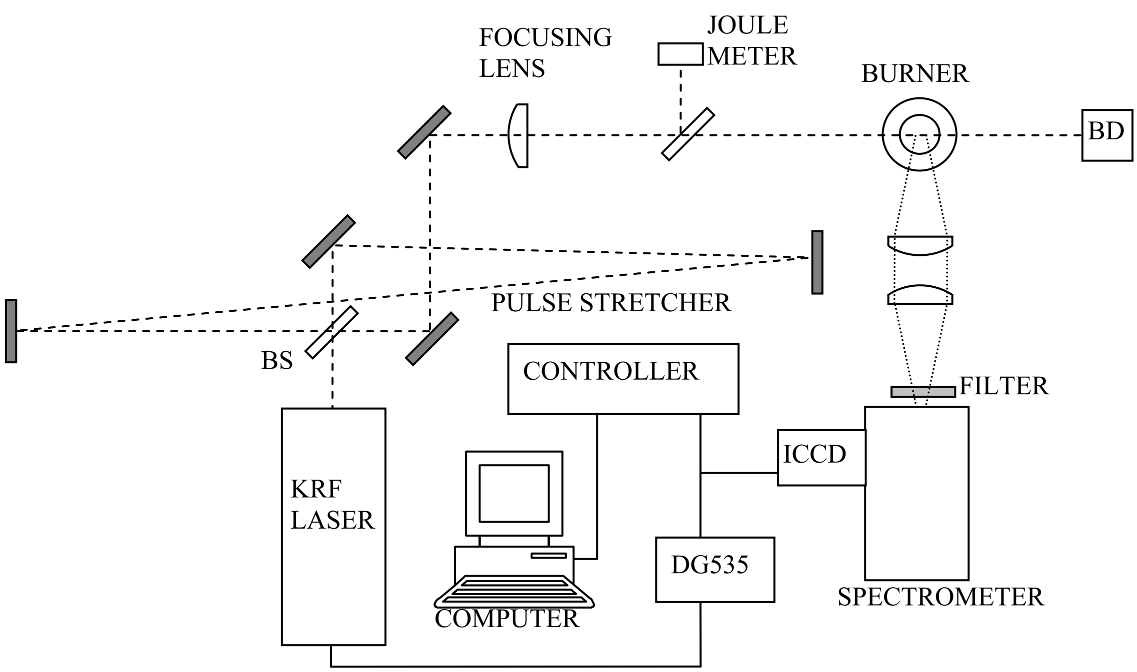


Figure 1. UV Raman setup.

## III. EXPERIMENTAL RESULTS

### A. Spectra of surrogate fuels

A typical surrogate fuel mixture that represents cracked JP-type scramjet fuel composition includes hydrogen ($H_2$), methane ($CH_4$), ethane ($C_2H_6$), ethylene ($C_2H_4$), propane ($C_3H_8$), and propylene ($C_3H_6$) (Puri et al. 2005). We examined Raman spectra of methane, ethylene, and propane using a Hencken burner (12.5 mm diameter multi-element matrix surrounded by a 4.3 mm wide $N_2$ co-flow annulus). Either pure fuel or fuel mixed with air, both without reaction, is used, and their spectra are compared with each other (Fig. 2). The laser energy was 400 mJ/pulse and the pulse is unstretched (20 ns). These are single-pulse spectra for a 0.2 mm line length. The results show that methane and propane are essentially interference-free in room temperature conditions. Ethylene fuel is used in this work and some overlapping between oxygen and ethylene Raman signals is observed, but in principle it can be accounted for in the data reduction procedure by using a different Raman signature for ethylene.

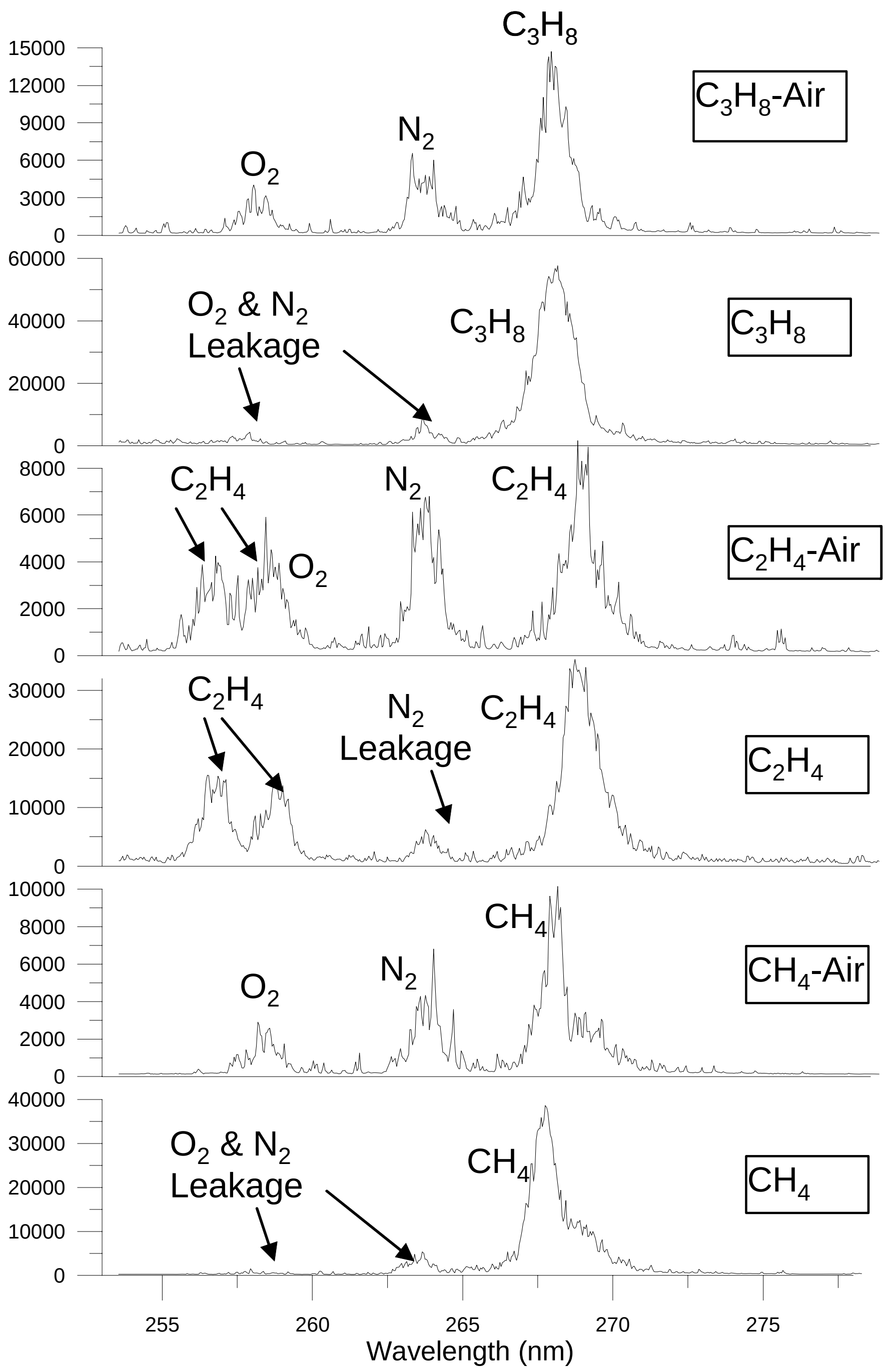


Figure 2. Sample single-shot Raman spectra of selected surrogate fuels (T = 297K)

The single-laser shot Raman spectra for room air is shown in Fig. 3. The laser is focused to a 0.2 mm beam diameter and a 0.2 mm beam length is measured. The laser energy is 400 mJ/pulse and for this measurement the laser pulse is not stretched (and thus the width is 20 ns). The maximum camera counts per species are approximately as follows: 18,000 for $O_2$; 37,000 for $N_2$; and 2,800 for $H_2O$. The background is at 230 counts.

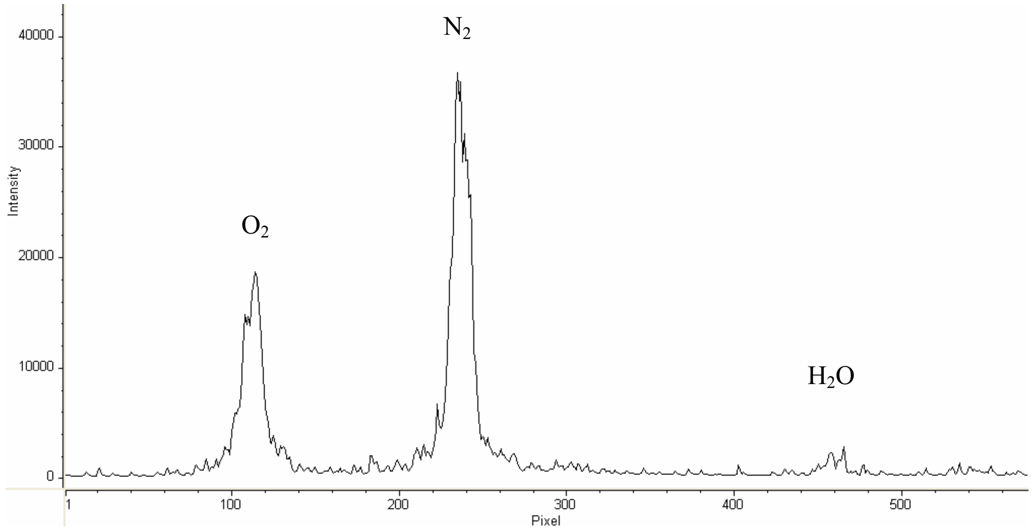


Figure 3. Sample single-shot Raman spectra in air (T = 297K).

In single-pulse spontaneous Raman scattering measurements, the dominant noise source is shot noise. For an ICCD camera, the signal-to-noise ratio is $SNR = \sqrt{\eta N_{pp} / \kappa}$ where $N_{pp}$ is the number of photons from the measurement volume that strike the photocathode, $\eta$ is the quantum efficiency and $\kappa$ is the noise factor (Paul, 1991). For the current Princeton Instruments camera, $\kappa \approx 2$ and $\eta = 0.25$. The number of photoelectrons, $N_{pe} = \eta N_{pp}$ can be estimated from Figure 3. The $N_2$ line has a half-width of ~15 pixels and a peak of 37,000 counts giving a total of 555,000 counts. The camera is set to its maximum gain of 72 counts per photoelectron giving $N_{pe} = \eta N_{pp} \approx 7700$ and SNR $\approx$ 60. Thus in room air for 0.2 mm spatial resolution, the UV Raman system can measure the $N_2$ concentration to better than 2% precision for a single laser shot.

## B. Application to a Mach 2 air flow over a piloted cavity

To apply the UV Raman system to the Mach 2 flow over a cavity, the system was transported to Research Cell 19 in the Propulsion Directorate at Wright-Patterson Air Force Base, Ohio. A picture of the UV Raman system applied to make measurements in the Mach 2 flowfield is shown in Fig. 4. The two spectrometers and light collection system are shown mounted to a translation table below the wind tunnel. A 5 meter laser focusing lens was used to avoid damaging the windows. The 5 meter lens focuses the laser beam to about 1 mm in diameter in the combustor. The laser pulse is stretched from 20 ns to 150 ns using two optical cavities shown in Fig. 1. The laser energy was also reduced to 100 mJ/pulse to avoid window damage. In addition, a thin film polarizer was used to dump the polarization component of the laser pulse that did not contribute to the Raman scattering signal. All of these efforts allowed the KrF excimer laser to pass through the fused-silica side windows without producing any damage. Also shown in Fig. 4 is one of two alignment apertures (aluminum disks with 2.4 mm diameter holes) used for ensuring that the beams remain along a path that defines the desired probe region; this enabled assessment of the alignment during wind tunnel measurements and quick realignment.

The schematic of the air flow over cavity with back ramp and a centerline strut is shown in Fig. 5. The tunnel has a two-dimensional Mach 2 nozzle. The air flow rate was about 1.4 kg/sec. Fused-silica windows (Suprasil, with good transmission at 193 nm) form the side walls of the tunnel. The tunnel has a constant-area “isolator” section upstream of the cavity with a cross-section of 51 mm high by 153 mm wide; downstream of the isolator, the bottom wall diverges at an angle of 2.5°. The cavity provides a region for a flame pilot and it is 17 mm deep and 66 mm long. A shear layer forms at the edge of the first step in the cavity and the recirculation zone is produced by the cavity. The region behind the strut mixes fuel and hot products from the cavity with the incoming flow.

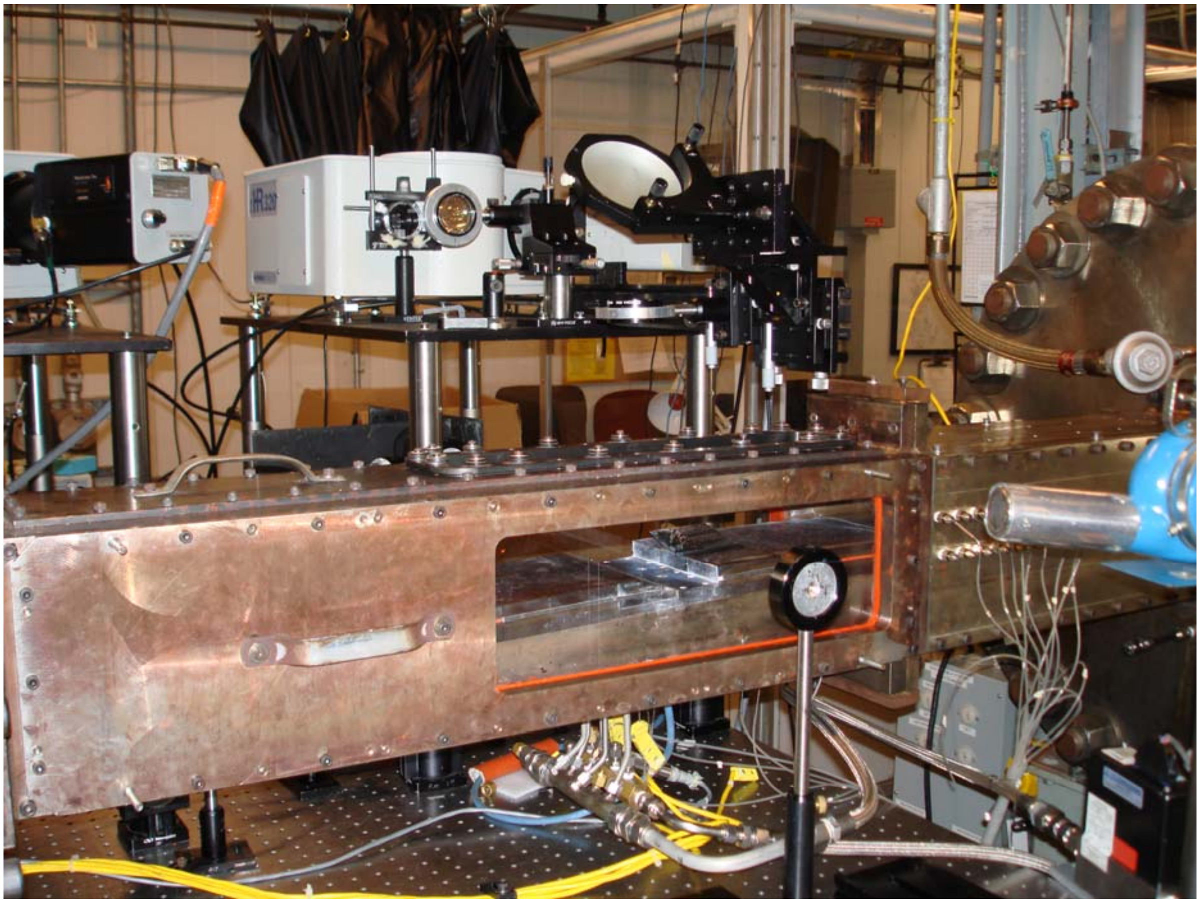

Figure 4. UV Raman setup at Research Cell 19, Propulsion Directorate, AFRL, WPAFB. (The flow is from right to left).

Mach 2 Flow →

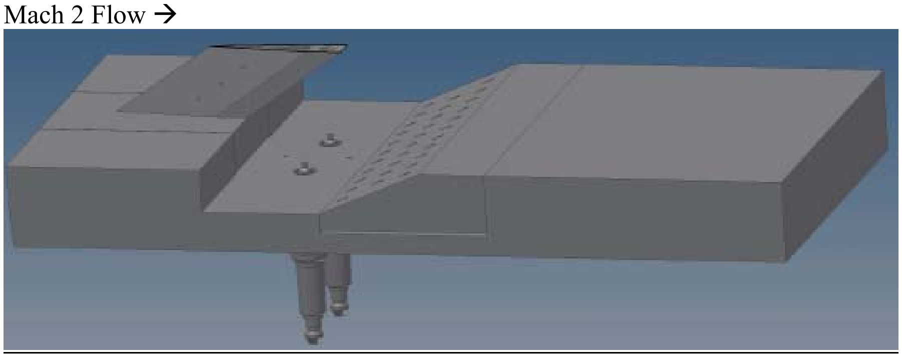

Figure 5. Mach 2 air flow over a cavity with a back ramp and a centerline strut.

The laser beam passed through fused-silica windows on the side walls. The Raman spectra were measured through the top fused-silica window using the same optical system shown in Fig. 1 and pictured in Fig. 4. Measurements of the Raman spectra of room air were made in the tunnel and are shown in Fig. 6. A Raman image is shown that is an average of a few hundred laser pulses. Below the image is a line Raman spectrum that averages across the spatial dimension. Note that the lines are broad as a consequence of the larger beam spot size (~1 mm diameter). Also, there is interfering light appearing to the right of the $O_2$ and $N_2$ lines (at $\lambda > 263$ nm). This obscures the $H_2O$ signal at 274 nm (see Fig. 3). This is laser-induced fluorescence from the fused-silica windows. This could be reduced by using low fluorescence fused-silica windows (fluorescence from one of the side windows was in fact worse than from the other).

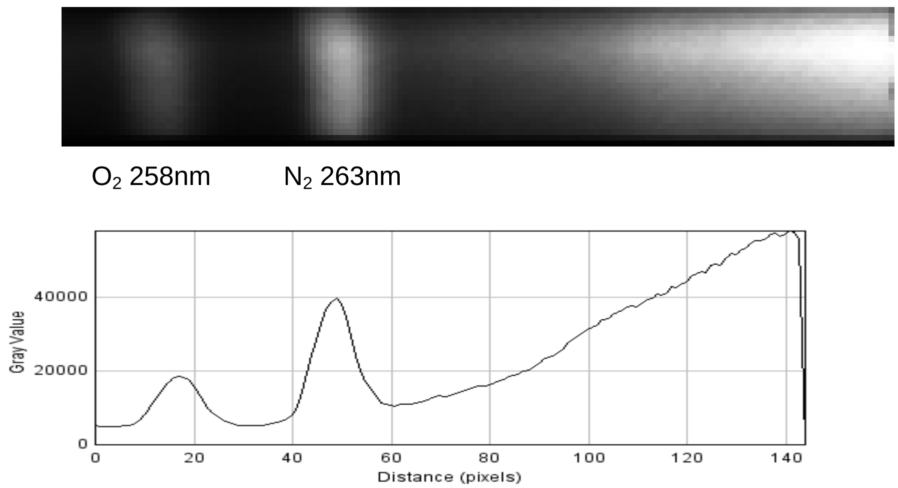

Figure 6. Raman spectrum of room air in the tunnel showing window fluorescence.

Raman images are taken in the fuel lean region of the flow above the cavity and behind the strut where there is only a small amount of fuel mixing with the incoming air. The cavity pressure is about 0.5 atm. Examples of the single-shot Raman spectra are shown in Fig. 7. In the top spectral image with combustion in Fig. 7a, the molecular species, $C_2H_4$, $O_2$, and $N_2$ can be seen. With no reaction in Fig. 7b, the Raman signals from $O_2$, and $N_2$ are stronger and the background laser-induced fluorescence from the windows is noticeable. The tunnel air without fuel injection shown in Fig. 7c looks about the same as Fig. 7b as this is a fuel lean region. The flame emission does contribute to the background in this fuel lean region as shown in Fig. 7d.

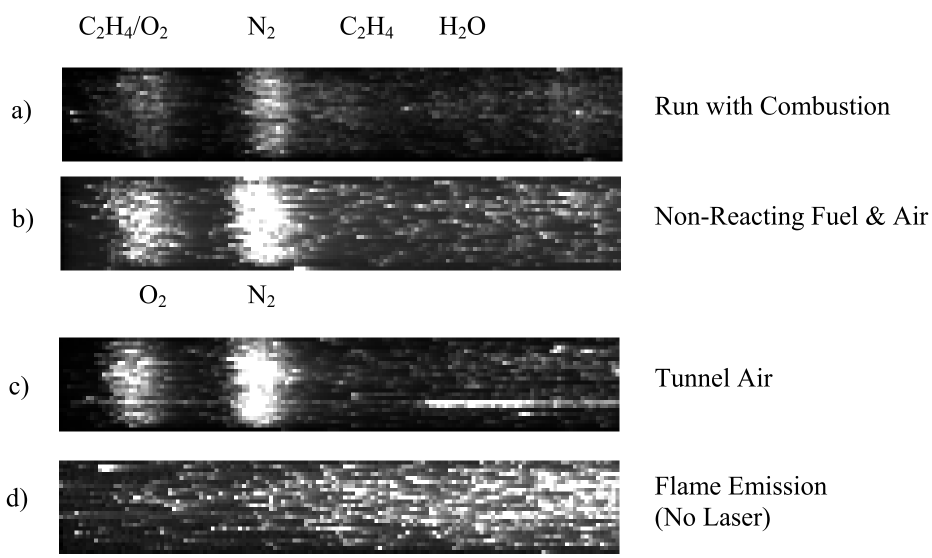

Figure 7. Single-shot Raman images in a fuel lean region of the Mach 2 flow over a cavity.

Raman measurements were also made in the fuel rich region as shown in Fig. 8. These single-shot measurements were made in the cavity where the $C_2H_4$ fuel is injected. As seen in Fig. 8a, laser-induced fluorescence of fuel derived species (such as polycyclic aromatic hydrocarbons) are seen. This laser-induced fluorescence appears as horizontal lines in the image. This interference obscures the Raman lines in the region. Also, “double” Raman lines appear. This is because under high Mach number conditions with combustion, the research cell heats up (because the walls of the test facility are about 500K). This causes the pulse stretcher optics to go out of alignment.[††] The pulse stretcher produces a number of pulses over 150 ns pulse length. When it is misaligned, the laser pulses pass through the combustor at two different positions. Because the entrance slit of the spectrometer was set to be larger than the laser beam width, both laser lines are imaged with the result shown in Fig. 8.

Under non-reacting conditions where the fuel has not reacted as shown in Fig. 8b, both the fuel ($C_2H_4$) and $N_2$ can be seen. This shows the mixing of fuel with air. The tunnel air signals without the fuel injection are quite strong as shown in Fig. 8c. In both 8b and 8c where there is no combustion, the background from window fluorescence can be seen. Finally, the flame emission in the UV region shown in Fig. 8d is quite strong.

Multi-shot measurements have been made at a number of locations and conditions. This data will be reduced to obtain information on fuel/air mixing and reaction in the piloted scramjet flowfield.

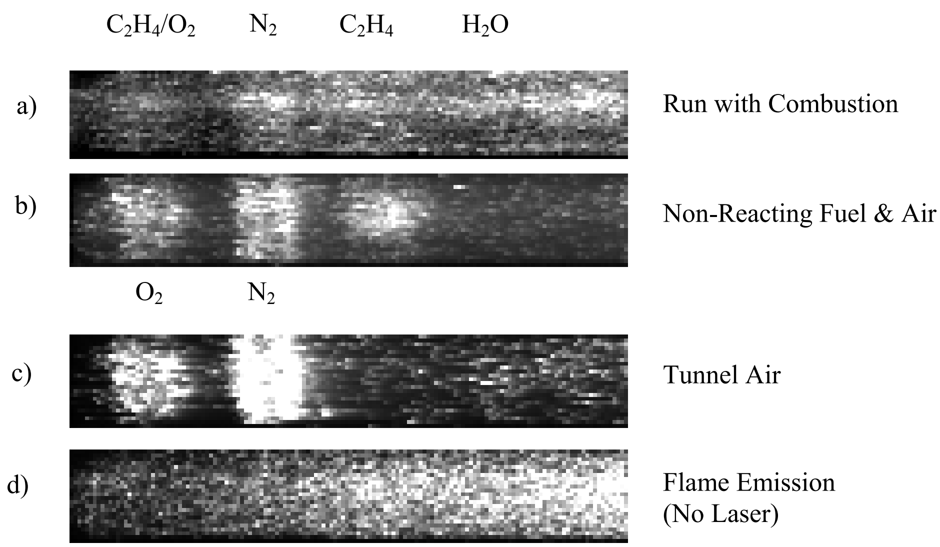


Figure 8. Single-shot Raman images in a fuel rich region of the Mach 2 flow over a cavity.

## IV. CONCLUSIONS AND FUTURE WORK

A line UV Raman system was developed for measurement of temperature and species concentrations in a scramjet combustor. The UV Raman system was transported to Research Cell 19 in the Propulsion Directorate, AFRL, Wright-Patterson Air Force Base. UV Raman spectral images of fuel and air mixing and combustion were obtained in a Mach 2 air flow over a cavity piloted with ethylene fuel. The Raman scattering was induced by a high pulse energy KrF excimer laser at 248 nm. The ultraviolet laser produces increased Raman signals as the Raman cross-sections depend on the laser frequency to the 4$^{th}$ power. The Raman measurements give concentration information of the molecular species: $CO_2$, $O_2$, $N_2$, $C_2H_4$, $H_2O$ and $H_2$. Temperature can also be determined. The laser pulse is stretched from 20 to 150 ns and only mildly focused in the combustor to avoid damaging the fused-silica side windows. Some problems were encountered in making the Raman measurements in the scramjet

[††] Following the work of Weir, Meier, Kutne, and Hassa (2007), we have recently replaced the two-cavity beam stretcher and 5 meter focusing lens with a pair of cylindrical lenses. Two 250 mm cylindrical lenses are perpendicularly arranged to give a soft focus of about 0.5 mm in the flame without damaging the fused-silica windows. With these cylindrical focusing lenses, the KrF excimer laser can be used with its normal output pulse (400 mJ, 20 ns) and not damage the fused-silica windows. With the removal of the two-cavity stretcher, the optical system would be much less sensitive to miss-alignment from heating. Furthermore, the intensifier gate time could then be reduced, suppressing the flame emission and other background light sources.

combustion flow. In rich regions, laser-induced fluorescence from fuel derived chemical species obscure the Raman signals. UV emission from the flame and laser-induced fluorescence from the windows contributes to the signal background. Furthermore, the heating of the ambient environment, concomitant with the preheated tunnel air, makes it difficult to keep the pulse stretcher in alignment. The Raman images will be reduced to obtain spatially resolved information on fuel/air mixing and reaction. Efforts will be made to improve the application of Raman scattering to scramjet flows including 1) replacing the beam stretcher/long focal length lens with a pair of cylindrical lenses[††], 2) replacing the fused-silica windows with low fluorescence versions, and 3) using fuels such as $H_2/CH_4$ blends that simulate cracked JP-7 fuels but produce reduced LIF interference in fuel-rich regions and flame emission.


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